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Technical Note Report

INVESTIGATION OF FUEL ECONOMY OF CONTAINER TRAILERS

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Abstract

Because port development consumes huge amounts of energy and materials, ports are one of the main sources of CO_2 emissions. For an exact estimation of the environmental impact, it is necessary to assess CO_2 emissions through the life cycle from material production, construction, usage, and maintenance to demolition. In particular, because infrastructure faciltities have a long life cycle, the usage stage plays a relatively large part. In this paper, fuel economy in transportation by a container trailer with a gross weight of over 10 tons is investigated in port areas and on the highway. The relation of fuel economy to travel speed and acceleration is also analyzed by estimating running resistance. The results show that fuel economy can be explained by the weight of a trailer and its average speed, and the relation among these factors is different depending on the road used.

KEYWORDS: *life cycle assessment, container trailer, fuel economy, runnning resistance*

1. Introduction

1.1 Background

Under the Kyoto Protocol, which will be soon effective, Japan is obligated to achieve a 6% reduction in greenhouse gas (GHG) emissions compared with 1990 in the 5-year period from 2008 through 2012. However, were already 8.0% higher emissions in 2000 than in 1990, indicating the need for immediate measures. Because port improvements accompanied by large-scale facility construction consume large amounts of materials and energy and emit large amounts of GHG, efforts to reduce these emissions are required. However, implementation of GHG reductions must be preconditioned on an appropriate estimate of emissions through the life cycle of the facility, from material production, construction, and usage to demolition. Because infrastructure such as port facilities has a longer life span than general industrial facilities, evaluation of the usage stage is more important. The factors in GHG emissions when port facilities are used also include the maintenance and operation of the facilities and transportation of containers. Transportation of containers includes

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marine transportation by container ship, inland transportation by container trailer, and container handling in the container yard. In this paper, inland transportation by container trailer is targeted (Figure 1).

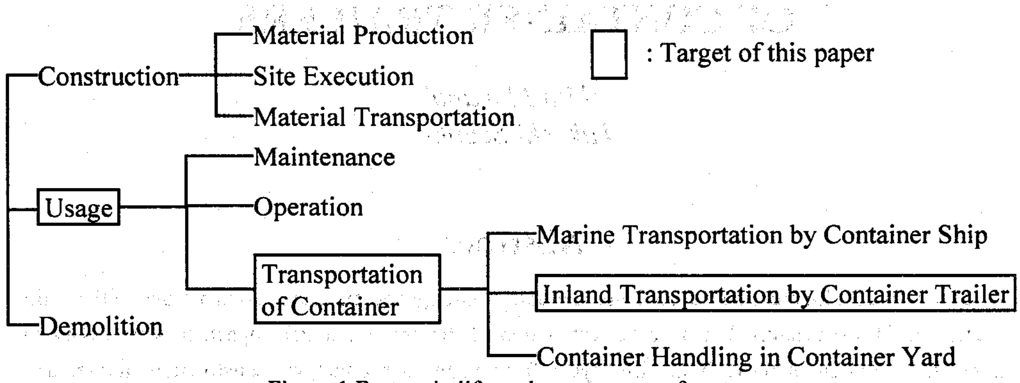

Figure 1 Factors in life cycle assessment of ports

When the fuel economy standard for a vehicle is prepared, the Ministry of Land, Infrastructure and Transport sets a mode showing the performance pattern and determines fuel consumption and exhaust gas composition on this basis. However, because the actual travel mode rarely corresponds to the assumed travel mode, actual fuel economy does not correspond to the published fuel economy.

Therefore, the effect of actual driving patterns on fuel economy has been researched. For instance, the effect of instantaneous speed and acceleration on fuel economy was investigated for an automobile and lightweight truck (Ahn et al., 2002). To facilitate such investigations, on-board measurement systems for vehicle exhaust and travel conditions were developed (Kondo et al., 2003). A simulation of the relation between average speed and fuel economy was performed for a medium truck from 2 to 8 tons in weight (Noda et al., 2004). In this simulation, the theoretical value of fuel consumption is calculated for combinations of engine speed (rpm) and load factor, and the ratio of engine speeds in various travel modes and the frequency of use at particular load factors was multiplied by the resulting values. As a result, all vehicles showed peak fuel economy at an average speed of 50-60 km/hr. However, analysis of vehicles with gross weights exceeding 10 tons has only begun (Gajendran et al., 2003), and no examples of research on container trailers exists.

In this paper, running experiments were performed for a container trailer that exceeds 10 tons in gross weight in port areas and on the highway, and the relation between fuel consumption and speed was analyzed by estimating running resistance. The results are expected to provide basic knowledge for the environmentally-sound design of port facilities, where large amounts of energy are consumed and large amounts of GHG emissions occur.

1.2 Elements Influencing Fuel Economy

To improve vehicle fuel economy, it is necessary to reduce the various kinds of resistance which occur during travel. Collectively, these resistance forces are called running resistance, and include rolling resistance, air resistance, hill climbing resistance, and accelerating resistance (Takehana, 1995).

(1) Rolling Resistance

Rolling resistance is the sum of all the resistance factors that occur because the tires roll on the road. It is caused by the warp of the tires and road surface, the roughness of the road, the sliding friction of the wheel bearings, and other factors. Rolling resistance R_r (N) is calculated as follows.

$$R_r = 1000 \times g \times \mu_r \times W \quad (1)$$

where W (ton) is the gross weight of the vehicle, g (m/s^2) is gravitational acceleration, and μ_r is a rolling resistance coefficient.

(2) Air Resistance

Air resistance is the resistance caused by the force of air acting on the vehicle body during travel. Air resistance R_a (N) is calculated as follows.

$$R_a = \frac{\rho}{2} C_d A V^2 \quad (2)$$

where A (m^2) is the frontal area of the vehicle, ρ (Ns^2/m^4) is the density of air, V (m/s) is the velocity of the vehicle, and C_d is an air resistance coefficient.

(3) Hill Climbing Resistance

Hill climbing resistance is the force that impedes hill climbing because the force component of the gross weight of a vehicle parallel to a slope acts in the forward and reverse directions as the vehicle climbs a sloping road with a gradient at a certain speed. Hill climbing resistance R_g (N) is calculated as follows.

$$R_g = 1000 \times g \times W \times \sin\theta \quad (3)$$

where W (ton) is the gross weight of the vehicle, θ is the slope angle, and g (m/s^2) is gravitational acceleration.

(4) Accelerating Resistance

Accelerating resistance is the force required to overcome the inertia of a car or truck traveling at a constant speed in order to accelerate the vehicle. Accelerating resistance R_{ac} (N) is calculated as follows.

$$R_{ac} = 1000 \times (1+\sigma) \times W \times \alpha \quad (4)$$

where W (ton) is the gross weight of the vehicle, α (m/s^2) is acceleration, and σ is the equivalent mass coefficient of rotating parts.

(5) Running Resistance

The running resistance R (N) when a car accelerates on a slope is the sum of rolling resistance, air resistance, hill climbing resistance, and accelerating resistance. It can be calculated as follows from the equation (1) ～ (4).

$$R = R_r + R_a + R_g + R_{ac}$$
$$= 1000 \times g \times W \left\{ \mu_r \cos\theta + \sin\theta + (1+\sigma)\frac{\alpha}{g} \right\} + \frac{\rho}{2} C_d A V^2 \quad (5)$$

To promote driving which reduces these resistance factors, automakers and transportation companies often hold fuel economy driving courses which recommend "Drive at an economical speed," "Avoid sudden starts and rapid acceleration," "Avoid unsteady driving," "Practice proper maintenance," and "Take advantage of inertia using the engine brake" as fuel economy tips. Interviews revealed that fuel economy improves 20-30% on average in test drives before and after training.

2. Methodology

Container trailer fuel economy experiments were conducted on October 21-22, 2002 and January 20-21, 2003, applying the same vehicle. An outline of the investigation is shown in Table 1. The main port areas were Ooi Wharf and Heiwajima in Tokyo. Highways included the Tokyo Metropolitan Expressway and Joban Highway. The vehicle used in the investigation was a container trailer with a head weight of about 6.6 tons. Its specifications are shown in Table 2. The weights of the chassis mainly used were approximately 3.7 tons for 40-foot containers and 3.5 tons for 20-foot containers. The weights of the empty containers were approximately 3.7-3.9 tons for 40-foot containers and 2.2-2.4 tons for 20-foot containers (Figure 2).

A fuel consumption meter to measure fuel consumption and a speedometer to measure speed were installed in the cab, and data were measured and collected as digital data. The fuel meter used here was a diesel type, which measures the flow of fuel into and out of the engine and calculates fuel consumption as the difference between the two. Fuel consumption can be measured in units of 0.05 cc/sec, and speed can be measured in units of 1 km/hr at 0.5sec intervals. For analysis purposes, the speed data were converted to units of one-second. Travel conditions were also photographed with a video camera to check the acquired data (Figure 3).

Table 1 Outline of investigation

Start Time	End Time	Gross Weight(ton)				Area
		Head	Chassis	Container	Total	
2002/10/22 7:00	2002/10/22 7:40	6.6	3.7	3.7	14.0	Highway
2003/1/20 13:15	2003/1/20 13:33	6.6	0	0	6.6	Port Area
2003/1/21 6:42	2003/1/21 7:27	6.6	3.8	2.4	12.8	Port Area
2003/1/21 8:30	2003/1/21 9:18	6.6	3.8	2.2	12.6	Highway
2003/1/21 9:47	2003/1/21 10:49	6.6	3.7	0	10.3	Port Area
2003/1/21 13:11	2003/1/21 14:14	6.6	3.5	2.3	12.4	Highway
2003/1/21 14:57	2003/1/21 15:30	6.6	3.5	12.7	22.8	Port Area
2003/1/21 15:30	2003/1/21 16:03	6.6	3.5	12.7	22.8	Highway

Table 2 Specifications of container trailer used in investigation

Model Number	KL-CK482BAT (manufactured in 2000)			
Size	Head	Length	mm	5,550
		Width	mm	2,490
		Height	mm	2,860
	Tread	Front	mm	2,040
		Rear	mm	1,840
	Minimum Road Clearance		mm	225
Weight	Vehicle Weight		kg	6,550
	Capacity		person	2
	Maximum Gross Weight		kg	39,520
Engine	Exhaust Volume		L	13.1
	Maximum Power		kW/rpm	294/1,900
	Maximum Torque		N·m/rpm	1,726/1,400

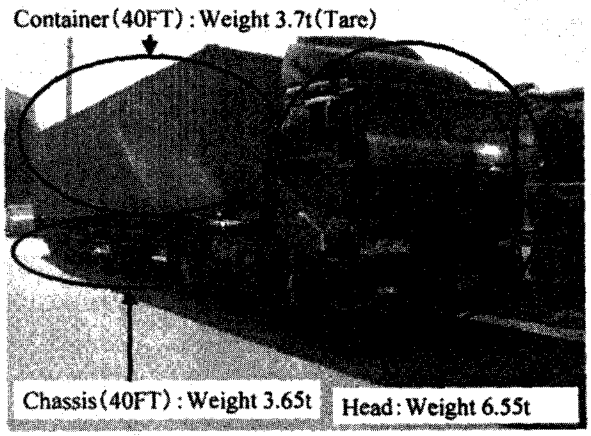

Figure 2 Container trailer used in investigation

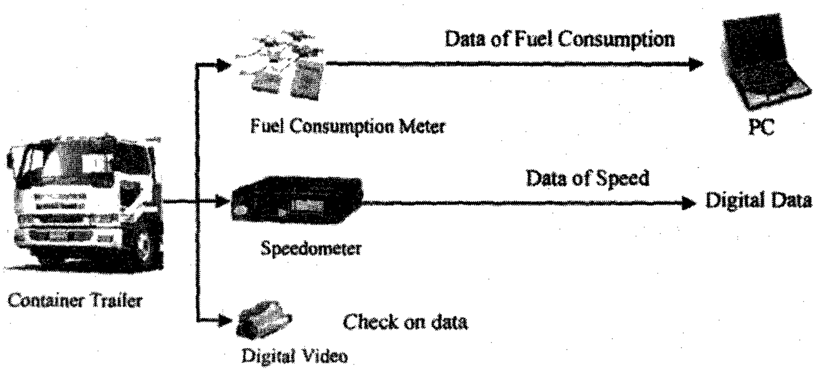

Figure 3 Devices used in investigation

3. Results

3.1 Time Distribution of Speed

The time distribution of speed in the investigation is shown in Figure 4. Parked time when the engine was stopped is excluded. As can be understood from the figure, in the port area, the vehicle was stopped (0 km/hr) for more than 1/4 of the total time. Time zones at 20 km/hr or less are the majority, and the average speed was 22 km/hr. In highway travel, it is thought that speeds of 40 km/hr or less accounted for nearly 20% of total time due to traffic congestion. However, in spite of some congestion, 80 km/hr or more accounted for more than half of the total, indicating that smooth travel was possible, and the average speed was 74 km/hr.

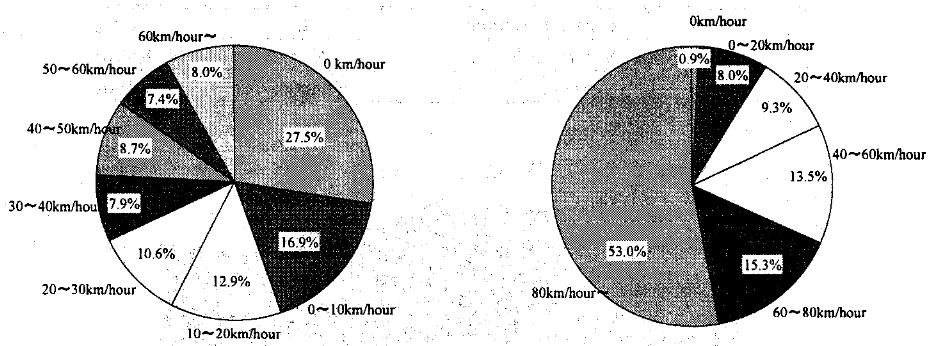

Figure 4 Time distribution of speed (Left: port area, right: highway)

3.2 Relation between Fuel Economy and Speed

First, for the port area, the relation between average speed and fuel economy at 300 sec intervals was plotted by gross vehicle weight, and the average values were then calculated by weight in 10 km/hour divisions (Figure 5). Generally speaking, the results showed that fuel economy decreased as total vehicle weight increased. Fuel economy at the gross weight of 6.6 tons was approximately three times that at 22.8 tons. This difference is also clearer in the intermediate speed range of 20-40 km/hr than in the low speed range of 20 km/hr or less. This is because the effect of weight becomes relatively smaller when the average speed is 20 km/hr or less due to the long stopped time in this range. From Figure 5, there are no large differences in fuel economy when the container trailer is traveling in the port area, even at different average speeds.

Next, the relation between average speed and fuel economy at 300 sec intervals was plotted by gross vehicle weight for highway travel, and the average values were calculated by weight in 10 km/hr divisions (Figure 6). No remarkable differences by weight can be seen in the high-speed range. The reason for this is thought to be that air resistance, which is not affected by vehicle weight, became the predominant factor in fuel economy. A detailed discussion of air resistance is presented in the next chapter. From Fig. 6, there is no large change in fuel economy in highway travel at different average speeds. Previous results for a medium truck 2-8 tons in weight showed that fuel economy peaks at an average speed of 50-60 km/hr (Noda et al., 2004). However, this does not agree with the results of this investigation. The cause will be discussed in the next chapter.

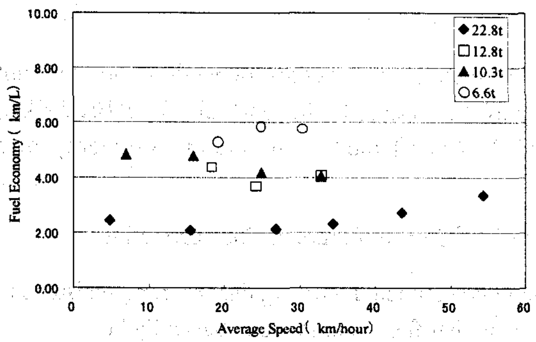

Figure 5 Relation between fuel economy and speed (port area)

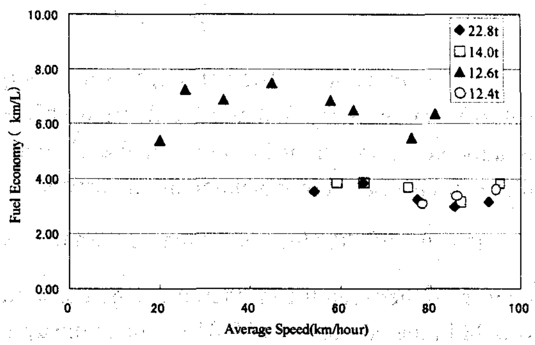

Figure 6 Relation between fuel economy and speed (highway)

4. Discussion

In this chapter, we will attempt a calculation of the running resistance which influences fuel economy and an estimation of fuel consumption based on the value.

4.1 Relation between Measured Energy Consumption and Estimated Work against Running Resistance

Work W_T (J) against running resistance R_t (N) from time $t=1$ to $t=T$, when a vehicle is traveling at speed V_t (m/s), where t (s) is elapsed time, is calculated as follows.

$$W_T = \sum_{t=1}^{T}(R_t \times V_t) \tag{6}$$

Assuming V (m／s) is average speed, the vehicle travels a distance of $V \times T$ (m) in time $t=1$ to $t=T$. W_L (J／m), work required to travel over a unit of distance, is calculated as follows.

$$\begin{aligned} W_L &= \sum_{t=1}^{T}(R_t \times V_t) \Big/ (V \times T) \\ &= \sum_{t=1}^{T}(R_t \times V_t) \Big/ \sum_{t=1}^{T} V_t \end{aligned} \tag{7}$$

W_L is calculated from eq. (5) and (7). As mentioned previously, running resistance is the sum of rolling resistance, air resistance, hill climbing resistance, and accelerating resistance. However, because only flat terrain was included in this investigation, the influence of hill climbing resistance is not considered here. The values used in calculations were rolling resistance coefficient $\mu_r = 0.01$, density of air $\rho = 1.225$ (Ns^2/m^4), air resistance coefficient $C_d = 0.75$, frontal area of vehicle $A = 2.49 \times 2.86 \fallingdotseq 7.1$ (m^2), and equivalent mass coefficient of rotating parts $\sigma = 0.15$.

Assuming fuel economy is F (km/L), the energy consumed in traveling 1 km E(J) is calculated as follows.

$$E = k \times \frac{1}{F} \tag{8}$$

where k is a coefficient expressing energy efficiency. k changes depending on the unit calorific value of the fuel and the thermal efficiency of the engine. In this analysis, 3.82(10GJ/kL) is adopted as the calorific value of diesel fuel, and 0.47 is adopted as the thermal efficiency of a diesel engine based on documentary materials.

The value of W_L (J/m) is compared with the value of E(J/m) in Figure 7. The correlation coefficient between the measured energy consumption and estimated work against running resistance is 0.88 in the port area and 0.81 on the highway, showing that fuel economy can basically be explained from a calculation of work against running resistance based on eq. (5) and (7).

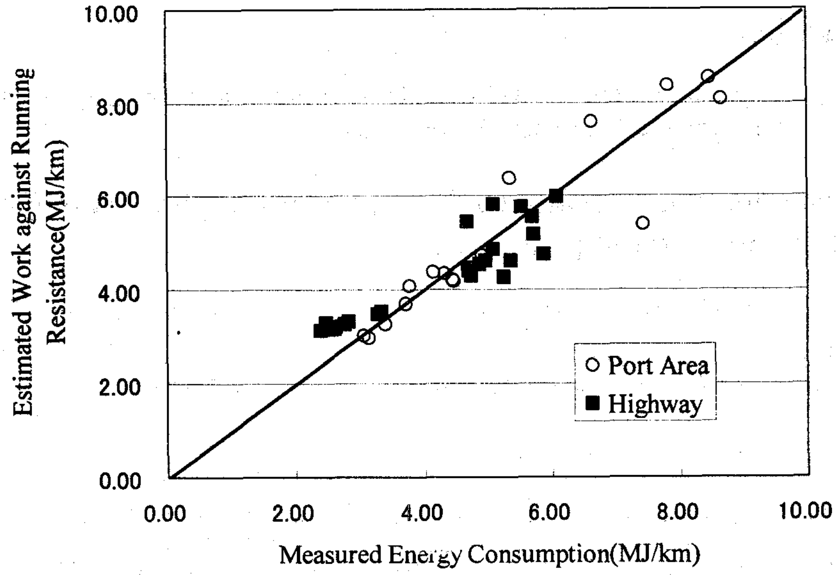

Figure 7 Relation between energy consumption and work against running resistance

4.2 Equation for Estimation of Container Trailer Fuel Economy

In this section, the average speed is assumed to be a variable, and an equation for estimation of the fuel economy of a container trailer is introduced based on an expression for estimation of work against running resistance.

(1) Equation for Work against Air Resistance

W_a, work (J/m) against air resistance for unit of distance, is plotted according to the average speed in (Figure 8). From this figure, it can be understood that work against air resistance can be approximated by one curve, with average speed as the variable, and is independent of travel in a port area or on the highway. The approximation equation can be expressed as follows, and the value of the determined coefficient is 0.94.

$$W_a = 7.9 \times V^{1.2} \tag{9}$$

Although air resistance is proportional to the square of the speed in the eq. (2), this is not the case in eq. (9). This may be because eq. (9) shows the mean value in a constant section while eq. (2) shows the instantaneous value.

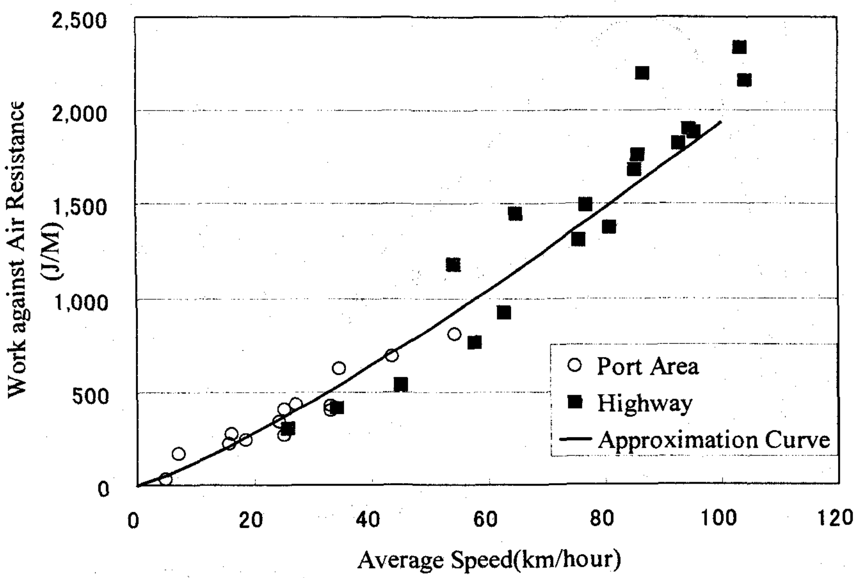

Figure 8 Relation between average speed and work against air resistance

(2) Equation for Work against Accelerating Resistance

From eq. (4), accelerating resistance is proportional to vehicle weight. To eliminate the influence of weight, the value of work against accelerating resistance divided by vehicle weight was plotted for each average speed (Figure 9). In highway travel, the data were divided into two groups (14.0t and 12.4t, 22.8t and 12.6t). The former can be considered a case of travel at high speed because the average speed of the entire trip approaches 100 km/hr. The latter can be considered a case of reduced speed due to road congestion.

The work load against accelerating resistance per unit of vehicle weight shows a general tendency to decrease monotonously as average speed increases. Therefore, eq. (10) is applied as a function that shows work against accelerating resistance per unit of distance.

$$W_{ac} / W = a \times e^{-b \times V} \tag{10}$$

where a, b are constants.

Although a comparatively high correlation was obtained for highway travel, this was not the case for port area travel. However, when eq. (11) was applied to port area travel, comparatively good agreement was obtained. Because data for average speeds of 20 km/hr or less do not exist for highway travel, it is difficult to judge the suitability of eq. (11). Therefore, eq. (10) is applied to highway travel. The values of a, b and the correlation coefficient in each case are listed in Table 3.

$$W_{ac} / W = aV \times e^{-b \times V} \tag{11}$$

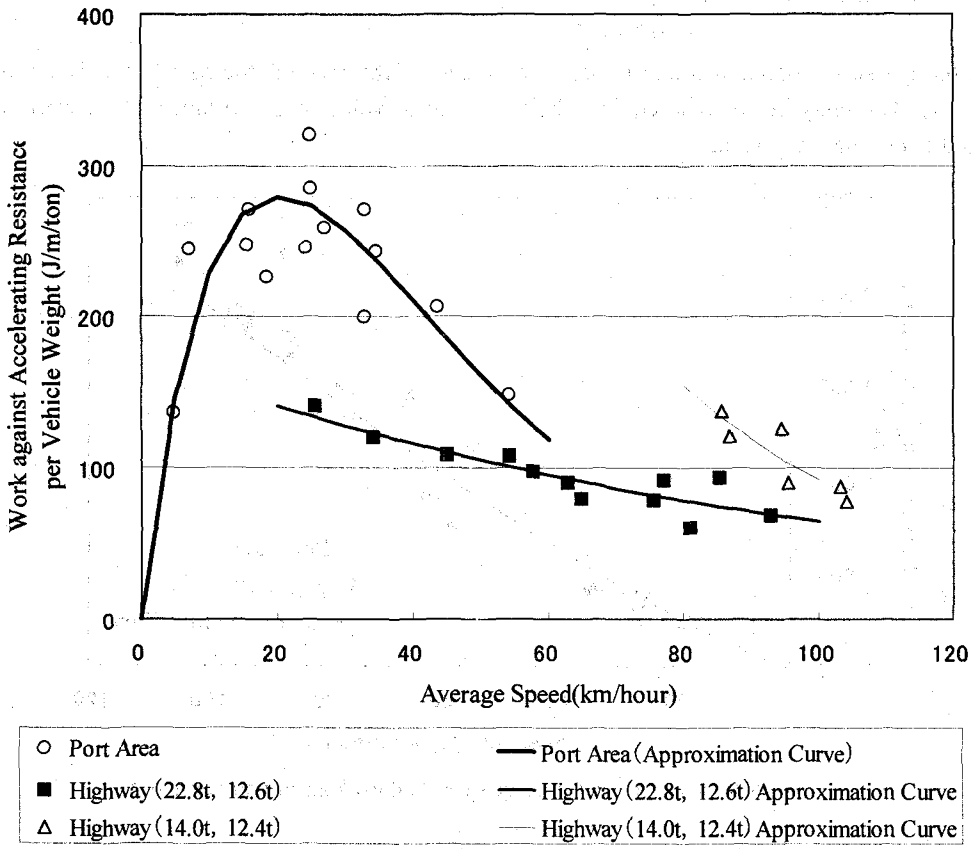

Figure 9 Relation between average speed and work against accelerating resistance

Table 3 Coefficients of equation for estimation of work against accelerating resistance

	a	*b*	Correlation Coefficient
Port Area	37	0.049	0.80
Highway(22.8t, 12.6t)	171	0.0097	0.87
Highway(14.0t, 12.4t)	1246	0.026	0.90

Eq. (11) has the feature of decreasing gradually when the average speed is high, but conversely, increases as the average speed increases when the average speed is low. The meaning of this equation can be interpreted as follows: When the average speed is low, stopped time is long and consequently, acceleration is relatively small. On the other hand, when the average speed is near the speed limit, the vehicle is traveling at a relatively uniform velocity, and in this case as well, acceleration decreases. Although this shows good agreement with the results of the present investigation, examination of its universality is required in the future

(3) Equation for Fuel Economy of Container Trailer

From eq. (1) , the value of rolling resistance is proportional to the gross vehicle weight and does not depend on average speed. Therefore, W_r (J/m), work against rolling resistance per unit of distance, can be expressed as follows.

$$W_r = 1000 \times g \times \mu_r \times W \tag{12}$$

where W (ton) is the gross weight of the vehicle, g (m/s^2) is gravitational acceleration, and μ_r is a rolling resistance coefficient.

Based on the above, expressions for estimating the fuel economy of a container trailer F (km/L) were prepared as follows.

Port Area

$$F = \frac{18000}{(37 \times V \times e^{-0.049 \times V} + 98) \times W + 7.9 \times V^{1.2}} \tag{13}$$

Highway (22.8t, 12.6t)

$$F = \frac{18000}{(170 \times e^{-0.0097 \times V} + 98) \times W + 7.9 \times V^{1.2}} \tag{14}$$

Highway (14.0t, 12.4t)

$$F = \frac{18000}{(1200 \times e^{-0.026 \times V} + 98) \times W + 7.9 \times V^{1.2}} \tag{15}$$

where W (ton) is the gross weight of the vehicle, and V (m/s) is the velocity of the vehicle.

The relation between the estimated and measured values of fuel economy is shown in Figure 10. The correlation coefficient was 0.94 for port area travel and 0.87 for highway travel, showing the validity of the equations for fuel economy. In urban areas, it is thought that fuel economy is reduced due to the large number of traffic signals, requiring frequent acceleration and deceleration.

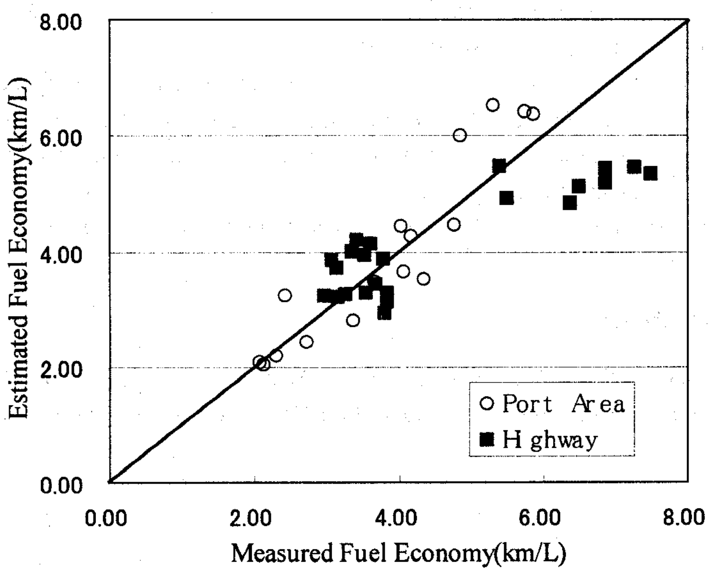

Figure 10 Relation between measured and estimated fuel economy

Future problems include improvement in the accuracy of the fuel economy equations based on a more detailed analysis considering the frequency and intensity of acceleration/deceleration.

5. Conclusions

In this paper, road experiments were performed with a container trailer with a gross weight exceeding 10 tons. The relation between fuel economy and speed was clarified by vehicle weight. The results showed a different tendency from that in existing research. However, it should be noted that these findings were obtained on limited routes in port areas and highways, and the experiments were conducted over a total of only 4 days. In addition, the driver displayed a high awareness of fuel economy in driving, which may have led to different results from the existing research.

The main conclusions are as follows.

1) When average fuel economy was calculated for various speed ranges, there were no large changes in fuel economy at different average speeds, either in port areas or on the highway. This is attributed to the fact that increased air resistance offset reduced accelerating resistance as the average speed increased.
2) A relatively high correspondence was found between the measured value of fuel economy and estimated work against running resistance, showing that fuel economy can basically be explained in terms of vehicle weight, speed, and acceleration.
3) Equations for estimating the fuel economy of container trailers were prepared assuming that vehicle weight and average speed are variables. When the estimated and measured values of fuel economy were compared, a relatively good correlation was obtained, showing the validity of the fuel economy estimation equations.

These results are expected to be reflected in environmentally-sound design of port facilities, contributing to a reduction in greenhouse gas emissions.

In this paper, only the relation between fuel economy and speed was analyzed. A more detailed analysis considering acceleration, engine speed (rpm), road gradients, etc. is needed. For application to policy, it is also necessary to compile unit values for environmental loads generated by transportation by container trailers based on these results. Problems for the future include contributing to the creation of port facility maintenance plans which consider the environment.

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